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After 40 Years Why Hasn't the Computer Replaced the Wind Tunnel?

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The debate between wind tunnels and computers to develop aeronautical systems has persisted for over 40 years. On the one hand, the majority of wind tunnels used today in aeronautical research, development, test, and evaluation were designed and commissioned in the 1950s and '60s. These facilities remain the backbone of the aeronautical development process, although they are becoming more challenging to maintain. On the other hand, rapid advances in computer hardware and software offer the potential to dramatically alter the design and development process for flight systems through the application of computational science and engineering. However, after 40 years of promises to eliminate the need for test facilities, advanced computational science and engineering have still not diminished significantly the need for test facilities or reduced the overall cycle time for development of flight systems. As many wind tunnel test hours are used today to develop a flight system as were used 20 years ago.

Key words: Aeronautical development; computational science and engineering; experience; high-fidelity modeling and simulation; performance prediction; physics modeling reliability; test facilities; validation & verification.

Now that I have your attention, the title of this article is actually the wrong question! The proper debate needs to be centered on how Computational Science and Engineering (CSE) and wind tunnel testing can be integrated to reduce the overall cycle time for development of an aeronautical system. If CSE could actually eliminate the use of wind tunnels in system development, the net gain to the acquisition program would be fractions of a percentage in cost savings. On the other hand reducing the overall cycle time by merging CSE and wind tunnel testing could reduce total development cycle time by months to years, resulting in billions of dollars of savings. This article is focused on understanding the challenges to using computational methods; delineating changes required in people, processes, and tools to make CSE more effective; and creating a vision for an integrated CSE/testing approach to reduce development cycle time.

First, for clarity, we need to define what we mean by CSE relative to the ubiquitous phrase "Modeling and Simulation (M&S)." For this article, we will focus our attention on high-fidelity, physics-based modeling and simulation as opposed to engagement or theater wargaming models. The former, which we will refer to as CSE, is more directly reflective of the aeronautical design process and the way test facilities are used to develop systems. The latter, which we will refer to as M&S, is more associated with doctrine, tactics and techniques, and training for the Department of Defense (DoD). Also, we will use the terminology CSE to connote that we are talking about the entire spectrum of physics-based modeling such as Computational Fluid Dynamics (CFD), Computational Structural Mechanics/Computational Structural Dynamics (CSM/CSD), computational electromagnetics, or computer-aided engineering. Embodied in these modeling activities are also computational heat transfer and chemical kinetics.

It is important for our discussion to maintain the distinction between M&S and CSE. M&S and CSE are both computational simulations, but within the upper levels of the DoD, M&S is ascribed to any and all computational simulations. In reality, the DoD focuses its management structure and funding on wargaming and training M&S. Aside from the activities of the Office of the Secretary of Defense (OSD) High Performance Computing Modernization Office (HPCMO), CSE has largely been left in the hands of Science and Technology (S&T), test and evaluation, and engineering function within the

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government as well as academia and industry. Consequently it has evolved in an ad hoc fashion, albeit with great success in select areas.

It is also important to understand the difference in the use of CSE in support of S&T and engineering. In the former, great strides are being made in the use of peta-flop (10^{15} floating point operations per second) computing in research approaching the molecular level. "Designer" materials are being developed by using computer simulations to manipulate molecules to achieve desired properties. While the S&T community has been the principal driver for advances in CSE, it has only been recently that the engineering community has become a key component of the CSE cognoscenti. In the past, the engineering design function has relied on legacy capabilities and relatively small computer systems. What has become clear in recent years is that a major justification for developing even larger scale computer systems is tied more to the engineering process than to the S&T community (i.e., the economic justification is based on the output of the product development process for commercial and military systems). The integration of multidisciplinary simulations and design optimization of aerospace vehicles throughout their mission profile is primarily an engineering function that can be enhanced by next generation CSE capabilities. It is also the engineering application of CSE that directly competes with engineering use of wind tunnels in the development process. In this article we will focus on engineering applications of CSE.

A celebration of success

Before we launch into a detailed discussion of why advanced modeling cannot replace testing in the near future, we need to understand that CSE has indeed had a profound impact on aeronautical system development. CSE is aggressively used by the aeronautical system design community to apply simpler engineering models to reduce the design space to a limited set of design variables that meet requirements. These select configurations are modeled with much higher fidelity physics-based models to develop prototype designs. Although these designs are not robust enough to eliminate the need for wind tunnel testing, they do reduce the need for multiple experimental configuration studies in the wind tunnel. Ironically, advanced computer-based control systems in modern military aircraft actually drive a need for even more wind tunnel data per configuration to ensure accurate control variables over the entire flight envelope. CSE is not currently capable of providing the control system inputs accurately enough to reduce the overall wind tunnel testing requirements.

Once the development phase starts into the wind tunnel phase, CSE is heavily used as a complementary tool with testing. Highlights from the application of CSE at the U.S. Air Force's Arnold Engineering Development Center (AEDC) in support of wind tunnel testing are summarized in Kraft and Matty (2005). Typical applications include pretest planning to ensure optimization of the test facility and instrumentation; support to real-time data analysis and decision making; analysis of potential wind tunnel effects such as support or wall interference; extrapolation of wind tunnel data to flight conditions; support to flight testing, particularly weapon separation; and support to operational flight issues that occur after a system has been developed. Also, CSE is an excellent tool late in the development cycle for evaluating incremental effects as well as anomalies that show up during flight testing.

To appreciate the impact of CSE on the aeronautical development process, a history of applications of CSE in support of wind tunnel testing at AEDC is illustrated in *Figure 1*. In the late '80s and early '90s serious engineering calculations were being performed even though the state of the art in computer capability was barely at the giga-flop (10^9 floating point operations per second) level. An inviscid, Euler solution for an F-15E aircraft complete with stores, pylons, pods, etc., using about 1 million grid points could be computed in less than 8 Central Processor Unit (CPU) hours, making it a useful engineering tool. The simulation, augmented and validated by wind tunnel data, was sufficiently accurate to predict the release of weapons from the conformal fuel tanks on the F-1 5E well enough to safely guide flight testing (Kraft 1994).

Using the 1988 calculation of the F-15E as a baseline, subsequent advances in CSE enabled more physics (unsteadiness and viscous effects) as well as refined grids to produce more accurate engineering solutions in less time. In *Figure 1*, complexity is defined as the product of the number of processors used times the number of grid points times the output in number of solutions per week. Most of the advances in capability demonstrated in *Figure 1* are attributable to rapid advances in hardware. Today, it is not uncommon to use 30–50 million grid points for a time-accurate, unsteady, viscous simulation of a complete aircraft and produce a solution in less than 8 CPU hours. These advances were made at AEDC, which has aggressively applied CSE to engineering problems for over 20 years but has relatively modest computing horsepower (Kraft and Matty 2005). Many of the solutions illustrated in *Figure 1* used only 32 processors, but today several hundred processors are available.

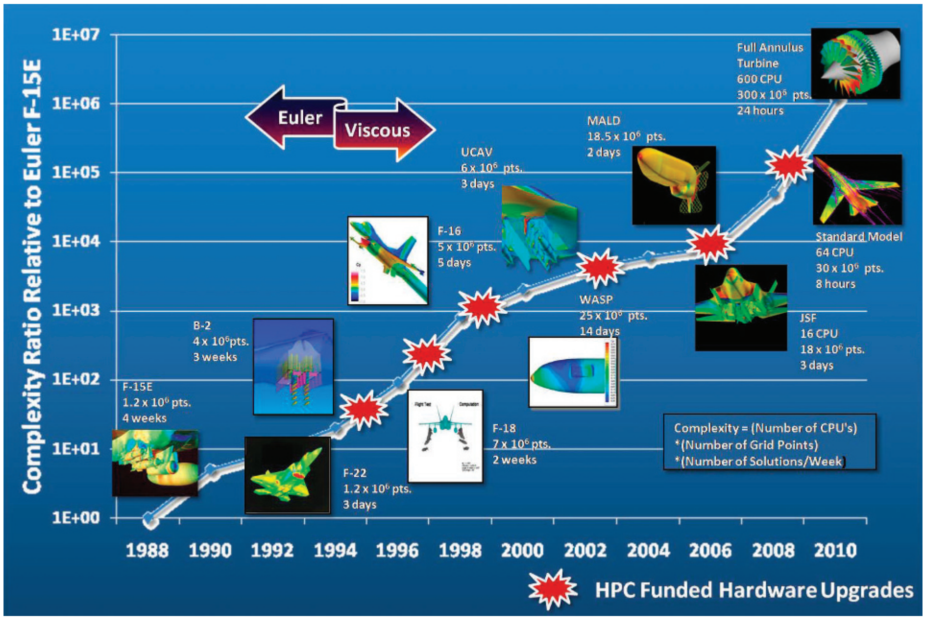

Figure 1. Increasingly complex computational fluid dynamics simulations enabled by computer hardware and software advances.

Some of the anecdotal success stories demonstrated with the CSE applications at AEDC represented in *Figure 1* include the following:

- F-15E—first demonstrated use of CFD to modify wind tunnel and flight testing resulting in safe carriage and release as well as improved operations for the F-15E. Post-integration of CSE with testing resulted in no flight incidents during certification of numerous weapons for carriage and release from the F-15E. The CSE tools developed for the F-15E have been persistently updated and applied to every DoD platform since, with immeasurable reductions in cost and improvements in safety.
- F-22—an integrated CFD/wind tunnel testing approach reduced the cost of models by over $8 million and provided insight to support an aggressive flight-test program for weapon separation clearance over the entire flight envelope with minimum sorties.
- B-1B (not illustrated)—CFD simulations of flare ejections eliminated a major part of a flight-test program at a cost savings of $500,000 to solve an operational problem.
- Minature Air-Launched Decoy (MALD)—CFD design of fins for use in the wind tunnel enabled high-quality data to be obtained in a smaller, more cost-effective wind tunnel.
- Joint Strike Fighter—CFD analyses enabled refinement of the inlet for the vertical or short take off and landing configuration during development, eliminated a wind tunnel entry for store separation simulation resulting in approximately $1 million savings, and augmented stability and control analyses.

There are numerous additional anecdotal accounts of how CSE has improved wind tunnel testing, but the real challenge is to develop an improved overall methodology for the use of CSE with testing to dramatically reduce the cycle time for development as well as improve performance of the systems. This article formulates the issues keeping CSE from having a larger impact on development and creates a vision for innovative ways to integrate CSE and testing.

Why hasn't CSE already replaced testing?

The "tastes great, less-filling" debate between CSE and wind tunnels has been ongoing for over 30 years). The classic American Institute of Aeronautics and Astronautics (AIAA) Dryden Lecture delivered by Dean Chapman in 1979 was the first serious salvo in the debate (Chapman 1979). Chapman's visionary article clearly identified the rapid growth in CFD hardware, software, and modeling capabilities that could transform the aerodynamic design process. Many of his CFD projections have been exceeded over the last 30 years. (He was forecasting breakthroughs only through the '90s and did not extend his vision to the scale of CSE today.) On the other hand, the average number of wind tunnel hours used in development of commercial and military aircraft continued to grow (Melanson 2008) over that same 30-year period despite wind tunnel efficiency increasing by at least a factor of four (Kraft and Huber 2009). At the same time, more and more DoD programs (and some commercial programs) overrun their original cost and schedule estimates. So what gives? Obviously CSE has not effectively changed the aeronautical development process to the degree envisioned by Chapman.

Very simply, advances in computers even to peta-flop (10^{15} floating point operations per second) performance and beyond are *necessary* but not *sufficient* to transform the aeronautical development process. It takes a holistic advance in the integration of people, processes, and tools to enable the kind of revolution people have envisioned for the last 3 decades. Even more than the tools, the people and processes need to be better understood and integrated with the advanced computer hardware and software to increase the effectiveness of CSE in the aeronautical development process. In the next section, we will explore challenges to the technologies, intellectual capital, and processes that will have to be overcome to achieve the full promise of CSE in the development process.

Technological impediments

Indeed, large-scale computing power is at our doorsteps. Although access to peta-flop computers is *necessary* for a revolution in applying CSE to aeronautical system development, it is definitely *not sufficient*. Having software that can efficiently and effectively use massive parallel computing power, having robust algorithms for complex and multidisciplined applications, improving modeling of essential physical phenomena, and systematically verifying and validating that the tools will work robustly in the engineering environment are equally important. In this section we will highlight some of these technical challenges.

Software scalability

The trend in high-performance computing architecture is toward massive parallel processing to upwards of 100,000 CPUs or cores. These trends are being driven by the rapidly growing cost of further increases in processor clock speed and the emergence of power density and cooling requirements as dominant considerations. High-performance computing centers are now requiring megawatts of power for operation. Although peta-flop computers are already available in select federal computing centers and exa-flop (10^{18} flops) machines are on the horizon, the legacy CSE software tools routinely applied to design and development problems have not been scaled to maximize the use and gain the efficiencies afforded by clusters with tens of thousands of processors. Most codes have been optimized to run on fewer than 100 processors. CFD solution algorithms tend to scale reasonably well, but many algorithms have topped out around 512 CPUs and only a few have operated with a few thousand cores. The very best CFD codes scale linearly to 5,000 cores, which is three orders of magnitude smaller than the potential million-core machines envisioned for the future. Even the highest performing CFD algorithms quickly lose ground when significant Input/Output (I/O) is required to grab and store solutions every few time steps for a graphical representation of an unsteady flow solution. Other CSE algorithms do not scale as well as CFD codes. Hence, even though peta-flop machines are becoming available, current software scalability limitations do not enable the solvers to use all of the hardware capability. One of the strategies to offset this near-term lack of scalability is to use a large number of available cores to simultaneously solve a number of parallel cases. This strategy will be useful in either rapidly reducing the design space in the early phases of concept development or in building a significant CSE data base in later stages of development.

Complexity

As computer systems have advanced, so has the complexity of aeronautical systems. Over the last 30 years, expanded flight envelopes, super-maneuverability, super-cruise, low observables, and advances in materials technology have made it more challenging to model the physics of military flight systems. As suggested in *Figure 1*, all of the advances in computer hardware and software have been absorbed in increasing the fidelity of more complex systems.

A significant challenge to developing a full flight system is the integration of the major subsystems (i.e., airframe/propulsion integration, airframe/structure integration, electromagnetic interference, control systems, and airframe/weapon systems). The major defects frequently found late in the development cycle for a flight system usually occur at the interface of major subsystems (e.g., aerodynamically induced structural failures). For example, on average for military aircraft, 10 structural flaws are found in the flight-test phase even after a comprehensive ground-test campaign and massive application of CSE. The fixes for these structural flaws can range from simple to significant, costing as much as $1 billion and delaying a program by a year or more.

Although significant advances in multidiscipline dynamic simulations for maneuvering vehicles have been made, the fidelity of current capabilities in terms of grid resolution, model complexity, and interdisciplinary coupling is still only a fraction of what is needed in the long run.

Performance predictions versus reliability

What is frequently overlooked by the CSE community desiring to replace testing is that test facilities are used to predict not only the performance, but also the operability, reliability, and maintainability of an aeronautical system. The majority of the ad hoc success stories in applications of CSE have to do with performance predictions only. CSE is not capable, for example, of simulating the aeromechanical performance of a turbine engine over its mission life to ensure that it will be reliable enough to field. It is also not capable of simulating the dynamic stressing of its structure to assure its reliability to stay "on wing" for hundreds of hours. Similarly, CSE is not robust enough to decide if an engine can be restarted at altitude or survive a bird strike or debris ingestion. Comparable limitations exist for modeling dynamic fatigue cycles for the aircraft structure. Historical data demonstrate that, on average, ten structural failures are discovered in flight even after numerous computer simulations have been performed. Consequently, in spite of advances in computer horsepower and applications of CSE, test facilities will be essential to assure a system is operable, reliable, and maintainable.

Physics modeling

The list of physics modeling challenges that inhibit the robust application of CSE is legend. The classical problems in applying CFD include turbulence modeling, boundary layer transition, and flow separation. For relatively benign attached or mildly separated flow, the use of Reynolds Averaged Navier Stokes (RANS) codes with the addition of large eddy simulations has advanced to a very good engineering capability but still has enough inaccuracy to preclude total reliance on the computed results. For vortex dominated or massively separated flows typical of advanced tactical aircraft at the corners of the flight envelope, the CSE tools are not nearly as capable. The dynamics of separated flow have a large impact on structural dynamics, stability and control, as well as control surface response.

Turbulence modeling may be one of those intractable engineering problems that cannot be solved with higher performance computing. Turbulence modeling in today's CFD codes is a semi-empirical approximation of the physics of turbulence to support practical calculations. To enhance predictions using turbulence modeling requires decreasing the size of the numerical grids. To double the resolution of a three-dimensional flow problem requires a factor of 16 increase in computer horsepower.

Although the promise of the revolution in computer hardware will enable this, the scalability of the software will make it challenging to fully utilize for realistic geometries. The step beyond turbulence modeling enabled by high-performance computing is Direct Navier Stokes (DNS) simulations. DNS does not make approximations to the equations of motion but does require a billion plus mesh point grids. Although research in this area is progressing for relatively benign geometries, it will be decades before DNS will be useful for relevant geometries of flight systems.

High-speed, hypersonic flight bring in another range of physics modeling challenges. At hypersonic conditions, additional physical phenomena such as real gas chemistry, conjugate heat transfer, wall catalicity, shock/shock interactions, etc., create significant problems for CSE. Compounding the physical modeling issue is the dearth of qualified experiments and test facilities to explore the physics and provide sufficient high quality data to validate and verify the models. For example, to fully benchmark hypersonic boundary layer transition phenomena would require experiments that encompass a wide range of Reynolds numbers, Mach numbers, angles of attack, bluntness, favorable and adverse pressure gradients, roughness, waviness, wall temperatures, cross-flow phenomena, surface catalicity, and a range of gas chemistries. Not to be overlooked is the requirement for advanced flow diagnostic tools that can be applied in the high-temperature, high-pressure hypersonic flight regime. A critical review of CSE and testing for hypersonics, presented in Kraft and Chapman (1993), suggests an incremental approach to CSE and testing to overcome the challenges to each.

Validation & Verification (V&V)

The aeronautics community has given itself one huge "head fake." There are numerous (and growing) conference articles showing "good" comparisons between CSE solutions and select experiments. These comparisons have been the basis for many marketing efforts to try to make the argument that CSE can duplicate test facilities. However, an accumulation of anecdotal comparisons does not result in a robust tool. Tinoco (2008) probably expressed it best:

> *"CFD validation cannot consist of the comparison of the results of one code to those of one experiment. Rather, it is the agglomeration of comparisons at multiple conditions, code-to-code comparisons, an understanding of the wind tunnel corrections, etc., that leads to the understanding of the CFD uncertainty and validation of its use as an engineering tool. Examples include comparisons of predictive CFD to subsequently acquired test data. The question is not can CFD give a great answer for one or two test cases, but can the CFD "processes" give good answers for a range of cases when run by a competent engineer? This is what validation for an intended purpose is all about."*

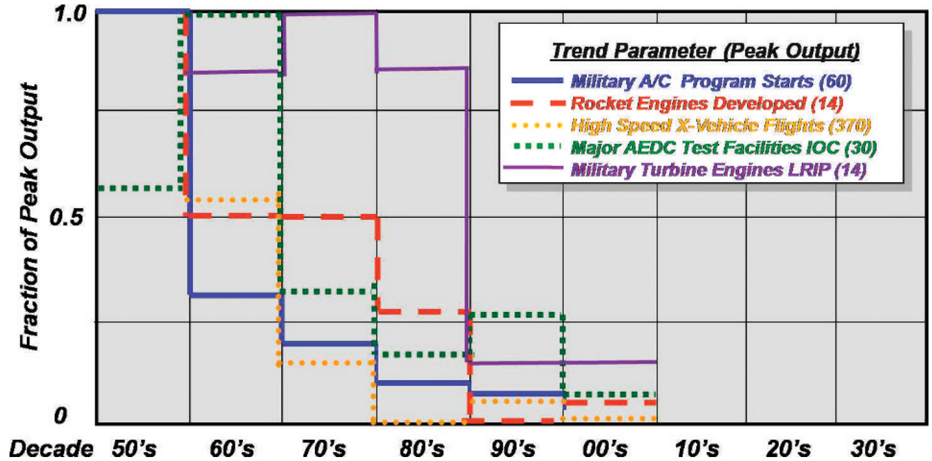

Figure 2. Experience trends in aerospace systems development—reduced opportunity for development of intellectual capital.

The recent AIAA drag prediction workshop compared results from a number of state-of-the-art codes applied by experienced CSE practitioners to the prediction of drag on transonic transport aircraft configurations (Vassberg et al. 2008). The workshop provided a very broad view of the state of the art of CFD applications within the industry, much more so than that which can be garnered by an isolated study. In fact, by reviewing in isolation any one of the individual data blocks, one may arrive at different conclusions from those determined from the complete data set comparison. For example, a typical publication may show how successful a CFD solution matches test data. By combining a large set of solutions from many sources around the world, this workshop clearly showed that there remains much room for improvement.

The need for robust V&V also underscores the requirements to put error bars on the computational results as well as the experimental results. However, one must exercise caution in doing so. A CSE solution, since it is deterministic for a given computation, will have zero precision errors but could have excessive bias errors driven by grid resolution, time steps, numerical dissipation, boundary conditions, and physics modeling. On the other hand, experimental data can have both precision and bias errors. Precision errors at the 95% confidence level are usually well documented in the experiment, but attention needs to be paid to bias errors driven by geometric modifications of a scaled model, Reynolds number scaling, wall interference, support interference, etc. Experimental validation data for CSE V&V needs to be well documented for precision and bias errors. Furthermore, comprehensive V&V of CSE needs clear identification of all boundary conditions, which will require off-body flow measurements for completeness of the experimental data base.

Experience and intellectual capital

Increasing the use of CSE versus testing is a two-edged sword relative to the technical talent involved in aeronautical system development. On the one hand, visual output from high-fidelity models provides unprecedented insight into flow features that cannot be obtained in any other way. Being able to "see" streamlines and vortex patterns on flow over a vehicle brings new understanding in the causative relations between aerodynamic shapes and vehicle performance. The tools also allow relatively rapid evaluation of changes to the design, which in its own way introduces more insight. On the other hand, having a generation of engineers experienced only in the "zeros and ones" of advanced modeling has the downside of limiting real understanding of the physics of the problem, especially when extending into realms beyond the physical fidelity of the model. The experiential insight gained from physically measuring phenomena is important in two ways—it provides more depth in understanding and is absolutely essential to guide development of models to capture the physics. There seems to be a circular argument that we can better model the physics than the experiments when the models are only as good as our physical understanding gained from experiments. If we no longer have experimental facilities, how do we advance the physical representation in the models?

It is painfully apparent in the aerospace industry that there has been a significant decline in the experience base of aeronautical designers and developers. As shown in a RAND study, the experience base for post–World War II engineers was approximately 6–12 new design aircraft per career (Drezner 1992). The number of new military aircraft program starts per decade is shown in *Figure 2*. In the 1950s there were 60 aircraft programs in various stages of development.

In contrast, aerospace engineers starting their careers today may experience only one, maybe two new system designs during their careers. The decadal decline of career opportunities in other aerospace technical areas is also shown in *Figure 2*. For most aerospace systems such as rocket engines, turbine engines, high-speed X-vehicles, and ground-test facilities, engineers today have far fewer opportunities to hone their skills than their predecessors. Anecdotal evidence has linked this trend to problems experienced in many recent aerospace development programs. Counterarguments point out that rapid advances in design, manufacturing, and information technologies used in the design and development process of today's new design aircraft have compensated for some or all of the declining experience base.

A study was performed at the Massachusetts Institute of Technology (MIT) to understand whether the application of large-scale computer simulation to the design process would offset the inexperience of aircraft designers (Andrew 2001). The study explored results from multiple aircraft programs covering 4 decades from the '60s through the '90s. Aircraft weight management through the development cycle is a critical and well-documented parameter that can be compared from program to program and decade to decade. In the study, there was clear evidence that weight management degraded from decade to decade and was clearly linked to the level of experience of the designers. Key findings from the study included the following:

- Strong linkage exists between experience and performance.
- Seventies-era design efforts outperformed '90s era in weight management.
- Test phase is an important downstream indicator of design performance—test personnel understood design flaws through exposure to recurring problems
- Modern design tools are graphically compelling, but reduced experimental experience led to deficiencies.

While simulation and automation of the design process certainly helped, it did not substitute for the intuition and inspiration that contributed to successful new and innovative designs. Also, such automation was only marginally effective when dealing with new and untried technologies because the basic information needed for the computational algorithms was missing or of low fidelity. Furthermore, it should be clear that one cannot really assess a design only on the computer. One has to build the prototype and test it, otherwise design flaws will flow downstream into manufacturing and operations. The earlier that design flaws are discovered through prototype testing the better.

In the MIT study, some negative effect was found to be associated with today's computational tools. Not so much the tools themselves, but with regard to the tacit knowledge derived when interacting with them. Today's tools are much less effective at developing the tacit knowledge of the users. Sophisticated simulation models of all types, some with realistic graphic presentations, seem to command a greater level of creditability than they deserve in many cases. In digging for a root cause to some design issues, it was clear that there were significant shortcuts taken with respect to supporting wind tunnel testing and modeling efforts needed to develop a model worthy of the level of confidence with which it was being applied.

It is hard to envision that the late Richard T. Whitcomb of the National Aeronautics and Space Administration (NASA) Langley Research Center would have made his breakthrough contributions to aerodynamics if the only tool he had was a computer. His insights into transonic area ruling, supercritical airfoil sections, and winglets came about by persistent experimental research and sound physical understanding of the flow phenomena (Hansen 1986). The three-legged stool of theory, experiments, and computations is necessary to make real advances in the aeronautical sciences.

Processes

CSE is just a single tool in the systems engineering process required to design, develop, and field an aeronautical system. Consequently, if the CSE community and its practitioners are not equally fluent in understanding the overall processes, CSE will generally not have the desired effect on overall development. Ensuring the process environment is conducive to integration of CSE may be the single most important consideration for advancing CSE!

Cultural acceptance

The application of CFD to aeronautics over the past 40 years has seen some interesting dynamics in acceptance by the community. In the early '70s when CFD was just emerging as a viable tool for augmenting aeronautical development, the "young Turks" engaged in its development were enthusiastic about its potential. However, the managers making decisions at that time had not grown up in an environment of CSE and were not prone to support a large scale application of CSE. In reality the tools were not quite mature enough to have a major effect.

After a generation of CSE fledgling applications, the original "young Turks" became the mid-level decision makers in the '90s and were influential in increasing the applications of CSE. They were the zealous advocates for CSE being able to replace or reduce the need for traditional development tools such as testing. However, by the early 2000s, it was painfully obvious their predictions were not coming true, leading to a backlash in credibility for M&S.

Why didn't they succeed? Simply, they oversold the capabilities of CSE. In their enthusiasm for its technical potential, they underestimated the people and process issues discussed in this article. Also, in the '90s the DoD, recognizing the potential ascendance of M&S, decided to organize their efforts. The DoD, however, largely organized and funded M&S for wargaming and training, which left CSE (as we use the terminology in this article) to ad hoc development by the research and engineering communities. Although highly successful in support of wargaming and training, M&S is not appropriate for modelling physical characteristics of material systems and hence has been unsuccessful in eliminating tests or reducing cycle time. Unfortunately, the limitations of M&S in supplanting the need for testing have produced a negative inference on CSE as well.

Another cultural dynamic that impedes the successful application of CSE to major programs is the lack of understanding that one needs to invest in a capability before taking the promised gains. It is not uncommon in the DoD to take the forecasted savings from M&S up front usually by diminishing the resources for testing. The need to invest in and implement the CSE tools to support the projected savings is usually not budgeted. As a consequence, the modeling and the testing efforts in support of system development both come up short, leading to further skepticism about M&S in general.

Finally, it needs to be recognized that the aeronautical development community is very conservative. Their design and development processes have been refined over generations of applications and are intended to reduce risks. Coupled with the forecast for fewer major aeronautical system developments, it will be challenging to have the industry perform a significant overhaul to their processes, no matter how attractive CSE appears. To further advance CSE into the development process will require a clear advantage to the program manager relative to better quality of data, lower costs, reduced risk, or reduced cycle time. Currently, shifting from testing to CSE is viewed as a risk without clear changes in quality, costs, or cycle time.

Concept of Operations (CONOPS)

Application of CSE in an S&T environment to a few predictions of the performance of a vehicle is woefully short of the operational needs required for the development of a system. The current operational model for large scale computers in the DoD and Department of Energy are suited best for S&T. To obtain access to the large number of processors needed to supply peta-flop computing for S&T, it is acceptable to queue up a number of very large batch problems and take days, weeks, or even months of "wall clock time." The engineering design and development process will require a significantly different CONOPS to succeed. In the early phases of design, literally thousands of configurations need to be evaluated quickly, albeit with simpler engineering models. As the design matures, a handful of parametric factors need to be evaluated with higher fidelity. As the design matures further, the data requirements rise exponentially. More data are required with very high accuracy on shorter cycles, and large databases need to be obtained for loads, stability and control, subsystem integration, flight simulation, etc. Quick turnaround computing to support interactive design is essential. This intensity of schedule, accuracy, and volume cannot be supported by competing in a queue with S&T projects (i.e., a dedicated facility will be required).

The dedicated use of engineering models in the very early phases of the design process will almost certainly be performed on proprietary systems within the aerospace industry. However, it is not envisioned that industry will invest in peta-scale computing resources even though the unit cost of computing is dropping dramatically. Industry chose to stay at modest levels of computing capability in the '90s and to rely on government investments to have access to larger systems (Mavriplis et al. 2007). Consequently, high fidelity peta-flop computer systems will be limited to a few federal sights for the foreseeable future. This could limit their application to developmental engineering without a better CONOPS. National capabilities may need to be scheduled for dedicated applications to major systems in development, much as government national wind tunnels are scheduled. There may not be enough peta-scale computing capacity at the national level to simultaneously support the S&T and aeronautical engineering community during a major DoD development. Also, these same large-scale computers will need to support other government acquisition programs such as naval ship design. Clearly, a strategy for providing sufficient capacity as well as a CONOPS to support design and development of systems will be required to enable any potential success for large-scale application of CSE to the development process.

Managing the process requires a monopsony

When trying to understand the reasons why high fidelity CSE hasn't had a larger impact on aeronautical system development, it is worthwhile to identify the common attributes of those areas where significant inroads have been made. It is the author's observation that CSE has had a significant impact on aeronautical system development in the following instances:

- The process is controlled by a single organization that can ensure the use of CSE in design and development.
- The organization has a substantial and sustained organic capability dedicated to building and applying CSE tools in a rigorous development process.
- The organization has at least de facto V&V of their tools as well as a sustained knowledge base of the lessons learned from the application of CSE across multiple systems.

Two pockets of success that meet these criteria stand out—design/development of commercial aircraft and the certification of air armament on military aircraft. The first case is obvious—a commercial aircraft company owns the entire design and development process, maintains its own data bases and tools as a competitive edge, and sustains a critical mass of experienced practitioners. Since the CSE tools are used consistently from program to program internally, there exists within the aircraft company a knowledge base on their use and their validity.

In the second case, the Air Force Seek Eagle process for certifying the safe carriage and release of air armament is the primary example. The AF Seek Eagle Office (AFSEO) owns the process for air armament certification recommendations. Consequently, AFSEO has complete control of the use of modeling, ground testing, and flight testing in the certification process. In conjunction with AEDC, AFSEO has aggressively developed and applied advanced CFD modeling to simulate the carriage and release of weapons from aircraft for over 20 years (Kraft 1994; Carlson, King, and Patterson 1995; Benek and Kraft 1996; Dean et al. 2007). The advanced CFD tools have been fully integrated with ground and flight testing to provide an effective approach to weapon separation (Keen et al. 2009). The community, now including the U.S. Navy (Cenko 2009), has developed a common set of tools, a library of grid models for important DoD aircraft and air armament, and a body of knowledge of CSE applications including validation and verification. This has culminated in the HPCMO-funded Institute for High Performance Computing to Air Armament Applications (IHAAA), which has built the tools, refined the applications process, documented a common models library, and created a critical mass of experts.

In the general development of military aircraft, there is not a single process owner. Although the Original Equipment Manufacturers (OEMs) have their own internal design capabilities used to support development, the development community at large does not have an integrated set of CSE tools. The OEM tools and databases are considered proprietary; hence they cannot be used by the broader community, particularly on different programs. In addition, the OEM tools have a wide range of levels of fidelity, different providers with different interface standards, a lack of rigor of recognized V&V, and an unwillingness to compromise. DoD acquisition policies introduced in the 1990s relinquishing total system performance responsibility to the OEM has been a major detriment to fully integrating CSE into the design and development processes for military systems.

Hence, to fully implement CSE into the design and development of military flight systems will require the government to create a *monopsony* (a single customer vice a single supplier as in a monopoly). The monopsony for design and development of flight systems will require

- government guidance on the systems engineering approach to design and development fully integrating testing and CSE;
- a common architecture for applied CSE enabling optimization for large-scale computing, multidisciplinary dynamic simulations, standard libraries and data bases for DoD systems;
- a modular "plug-and-play" environment permitting OEMs to use their own proprietary CSE tools, but in the common development process; and
- a critical mass of government CSE applications experts to ensure development and sustainment of the common architecture as well as provide the government the ability to perform independent assessment of OEM designs during the acquisition process.

Reengineering the aeronautical system development process to increase effectiveness

So we now come full circle. The proper national debate that needs to be held is not CSE versus test facilities. The aeronautics community would be better served putting their energy into creating a vision for how CSE can be integrated with physical testing processes to increase the effectiveness of both during the development of systems. Effectiveness in the context of this article means the ability to reduce the overall cycle time for development while minimizing the need for rework of late defect discoveries. The elements that need to be advanced to reengineer the aeronautical development process include CSE as well as test facilities. In addition, a vision needs to be created for innovative ways to bring CSE and testing together to have the maximum impact on the effectiveness of the development process.

The CSE tools that will enable a monopsony for aeronautical development are being developed under the OSD HPCMO Computational Research & Engineering Acquisition Tools and Environment (CREATE) program. CREATE is developing advanced modeling capabilities to support aeronautical, naval, and radio frequency design. CREATE-AV (air vehicle) is the aeronautical program under CREATE and is focused on the use of CSE tools across the entire spectrum of development and sustainment of aeronautical systems (Morton et al. 2009). By analyzing common computational needs for more than 20 acquisition program engineering activities from concept evaluation, system development, through implementation and sustainment, the CREATE-AV team has been able to determine a compact set of advances required in CSE. The CREATE-AV team determined there are four key software products needed by the acquisition engineering workforce that fit within the available budget and are accomplishable in the CREATE program timeline. The four software products are *Helios*, a virtual helicopter simulation tool; *Kestrel*, a virtual fixed-wing aircraft simulation tool; *Firebolt*, an airframe-propulsion integration simulation tool; and *Da Vinci*, a conceptual design tool. All four tools are currently under development.

An important CREATE software design philosophy that will support use by the community is modularity. A common architecture in CREATE-AV is a Python-based infrastructure and executive and either C or Fortran 90/95 components. This allows a build-up approach to adding capability and multidisciplinary physics. It also allows a factored approach to the software, aiding in code maintenance and supportability. This approach also allows all of CREATE to share components among software products to reduce the cost of development. Particularly noteworthy is an additional executables interface that would permit any proprietary computational module used by the OEMs to stay proprietary within their application, but make the output available to the government evaluation of the system performance.

Implementing new technologies to maximize effectiveness will require changes to test facilities as well. Furthermore, older facilities will eventually reach a point where they become too costly to sustain and upgrade, and building new is more cost-effective. However, when such thresholds are reached, these moments become opportunities to design from the outset facilities whose functionality reflects comprehensively our vision for how to conduct aeronautical ground testing. Kraft and Huber (2009) have created a vision for what future aeronautical ground test facilities need to look like to support better integration of CSE and to increase their effectiveness. Some of the attributes required for upgrades to current facilities or for future test facilities include:

- ability to install and de-install test articles in minutes to support high-frequency, short-duration tests focused in areas where primary uncertainties exist and to optimize use of Design Of Experiments (DOE);
- ability to rapidly prototype and manufacture models reflecting design changes that are instantly transmitted by customers of ground test facilities to their test partners using the latest in compatible CAD/CAM and model shop tools and materials;
- ability to efficiently modify test conditions or proceed through a test point matrix to minimize energy usage while reflecting to a maximum extent DOE considerations;
- convenient and thorough optical accessibility for flow diagnostics tools;
- connectivity to high-performance computing capabilities to integrate and merge CSE simulations and test data;
- advances in data mining and data merging software as an integral part of the facility data systems to enable rapid analyses of the variances along response surfaces; and
- virtual presence, networking, and connectivity to achieve a fully integrated Developmental and Operational Test (DT/OT) approach in an interoperable environment.

To bring CSE and test facilities into a unified toolset for streamlining the aeronautical development process requires a focus on effectiveness of the process, not just the efficiency of the tools. CSE has to be fully integrated with ground and flight testing to reduce the overall cycle time for development. Kraft (1995) introduced a holistic approach to integrating CSE with testing using a systems approach. Concepts evolved from the application of CSE to weapons integration led to a broader approach for acquisition programs by recognizing CSE as the potential unifying backbone for system knowledge management across the development cycle. The integrated approach described by Kraft (1995) reinforces the need to have a monopsony for managing the tools and knowledge across the entire development process to impact acquisition programs.

A primary objective measure for determining the effectiveness of the aeronautical development process is *acquisition cycle time*. Using CSE to reduce cycle time will have a greater overall influence on decreasing program costs and justifying CSE applications than any other cost-cutting strategy. Trying to justify CSE only as an offset to testing misses the best business case, since testing is only a small fraction of development costs. Reducing cycle time for major programs that can expend $1–3 million per day is much more cost-effective than reducing testing. Continued emphasis on the efficiency of producing data has marginal return on investment. For example, the cost of a wind tunnel campaign for development of a twin engine fighter is about 5 percent of the overall cost of T&E. In turn, the total cost of T&E for a development program is generally just a few percent of the total development cost. Hence, a 50% reduction in the unit cost of a wind tunnel campaign equates to just a few tenths of a percent reduction in program costs. Reducing cycle time by months can easily save a major development program on the order of $1 billion.

Cycle time can be estimated by the following relationship:

$$Cycle\ Time = \frac{Workload}{q \cdot Capacity}$$

In this expression, *Cycle Time* is the total time required for system development. *Workload* is the total amount of work to be accomplished (e.g., man-hours, test unit occupancy hours, data points, computed cases); q is a quality measure that indicates the fraction of the total work that is done right the first time (i.e., the inverse of late defects and rework); and *Capacity* is the amount of work per unit of time, which depends on the availability of the development infrastructure (testing and CSE), the staffing to use the capabilities, and the throughput. The three primary levers to decrease cycle time are reducing the workload required, minimizing rework, and increasing capacity.

The total workload involved in aeronautical system development is primarily process driven. For example, if a wind tunnel campaign for a major fixed-wing aircraft requires about 22,000 hours of wind tunnel testing, then given today's national capacity of about 6,000 h/y, such a campaign requires 3 to 4 years to conduct. Surprisingly, wind tunnel campaigns are traditionally designed around test hours, not test points. That is why a fourfold increase in productivity generated by the wind tunnel community in the 1990s had essentially no impact on reducing the number of wind tunnel hours for the F-35 program as compared with the F-22 program performed a decade earlier (Kraft and Huber 2009). Given more efficient throughput, the users of wind tunnels take more data, rather than reduce test hours. Anecdotal discussions with several aircraft companies over the years strongly suggest that a large fraction of the data acquired in the wind tunnel is not used but is retained as a "security blanket" in case an anomaly arises. Reengineering the way wind tunnel data are obtained and used has the potential to be a major driver for increasing the effectiveness of ground testing. Although CSE has perennially offered the ability to reduce overall workload, it has been offered as a replacement for testing. Currently, CSE as a direct replacement for testing cannot come anywhere near efficiently replacing the total wind tunnel and flight test hours.

Similarly, the inverse of q, the amount of rework normally performed, is also process driven. For most aerospace systems in development, q is approximately 0.25, resulting in four to 10 rework cycles. The incremental increase in program costs is proportional to $(1/q)-1$, indicating the potential to easily double development costs through late defects and rework. The best way to minimize the impact of rework on cycle time is early discovery of defects. This will entail improvements in design methodologies employed by aircraft companies coupled with improvements in wind tunnel testing and modeling techniques. These latter improvements minimize any defects in design being passed downstream to flight testing, where the cost of fixing the defect increases an order of magnitude. Also, feedback loops from discrepancies found in flight testing back to ground testing and back to design methodology need to be institutionalized to make further improvements. A primary target for decreasing rework is improving the early determination of the impact of steady and unsteady flow effects on the vehicle structure. Historically, most aircraft development programs have discovered 10 structural flaws in flight with varying degrees of cost and schedule impacts that can reach a billion dollars and a year to overcome. As can be seen from this example, increasing q (decreasing late discoveries) will have a profound effect on development cycle time and cost. The early reduction of defects may be the single most important area for the use of CSE. However, multidisciplined approaches will have to be improved to realize the potential gains in defect reduction.

In contrast to process-driven parameters, capacity is primarily budget driven. Capacity equals the availability of the capability times the staffing available to use the capability times the throughput. For testing, the availability of the equipment depends on investments in maintenance and reliability. Also, the budget determines whether a facility is staffed for one, two, or three shifts. Staffing is the most dynamic variable for increasing or decreasing capacity. Throughput (e.g., test points per hour, solutions per day) is also budget driven. The capacity of CSE is also budget driven. The availability of large-scale computers, the critical mass of intellectual capital to use the capability, and the throughput of the computations will similarly drive cycle time. Developing and funding integrated test facilities and CSE with capability and capacity optimized to maximize throughput using the reduced workload and defect avoidance and discovery approaches will be a powerful adjunct to process reengineering.

The discussion on cycle time focuses on the cycle time for testing. To aggressively attack the cycle time for development of a new flight system, one also needs to address the contributions to cycle time from design, prototyping, analysis of results, and other development and manufacturing maturation activities. There is potential interplay between these processes and those from testing that can further help reduce overall cycle time. In this article we are focused on reducing the equivalent cycle time for testing through better integration of CSE.

CSE does, however, offer significant potential to impact the overall wind tunnel campaign in three significant areas. First, and most importantly, CSE can be used to reduce the overall workload. Second, CSE, if applied appropriately, can reduce downstream effects of late defect discovery on total development cycle time. Third, CSE can be used to integrate major subsystems earlier in the development cycle avoiding late integration issues.

Minimizing workload

The primary target for reengineering aeronautical development to increase effectiveness is to reduce the overall workload without increasing risk. A major contributor to the number of wind tunnel test hours used is the need to generate about 2.5 million data points to determine the stability and control (S&C) of the vehicle. This is traditionally done in the one factor at a time (OFAT) mode where data are obtained for each model configuration, orientation, speed, and simulated altitude over the entire operating envelope. This ponderous number of data points also has been the primary reason that CFD has not made greater inroads into developmental wind tunnel testing. Estimates to compute the equivalent 2.5 million OFAT points range from approximately 100 to 1,200 years using existing computer tools.

Recently, the CFD community introduced an innovative and efficient computational method for accurately determining the static and dynamic S&C characteristics of high-performance aircraft (Dean et al. 2008). In contrast to the "brute force" approach to filling an entire S&C database for an aircraft, an alternate approach is to reduce the number of simulations required to generate a complete aerodynamic model of a particular vehicle configuration at selected flight conditions by using one or a few complex dynamic motions (e.g., varying frequency and amplitude over a dynamic trajectory) and nonlinear system identification techniques. This approach now makes CFD a reasonable source of S&C data for an aircraft.

Of interest, there is a comparable experimental technique using the pre-filtered dynamic output from the force/moment balance used in the wind tunnel, system identification techniques, and a "fly the mission" profile in the wind tunnel. Recent advances have been made in demonstrating control systems that permit a wind tunnel to respond in real time to changing Mach number and pressure altitude while maneuvering the test article to fly the mission versus building the massive data base using OFAT methods (Sheeley, Sells, and Felderman 2010).

As indicated in *Figure 3*, using these advanced "fly the mission" modeling and testing methodologies combined with design of experiments offers an innovative, aggressive approach to reducing the overall test workload. Attempts to apply DOE to streamline a traditional individual wind tunnel test have been only marginally successful because current wind tunnels are not conducive to rapidly changing parameters to optimize randomness of the data set. However, if one shifts to thinking about DOE at the "campaign" level there may be a more productive approach to using DOE.

Instead of the OFAT approach to building the colossal data base characteristic of today's aeronautical development processes, an approach using DOE response surface techniques could be more effective. A response surface is a mathematical construct that represents the parameter space along which the characteristics of the vehicle are captured. An example of the use of response surface modeling for aerodynamic configurations is given in Landman et al. 2007.

In contrast to traditional OFAT approaches that basically fill up the entire parameter space and try to interpolate to determine the characteristics of the vehicle, an initial response surface could be built using simple engineering models. Of course the uncertainty over the response surface would be high, but more refined high-fidelity physics modeling could then be efficiently applied to reduce the uncertainties over the response surface using the fly the mission approach

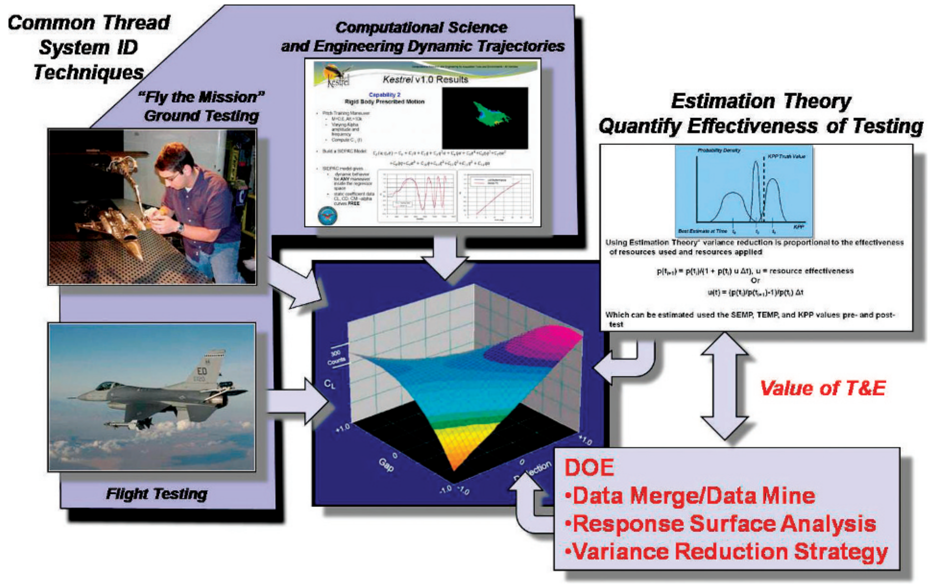

Figure 3. Streamlining the aeronautical development process by merging modeling and testing using design of experiments.

mentioned above. Those areas on the response surface that still exhibit a high degree of uncertainty then become the primary focus for the wind tunnel test campaign (i.e., the focus is put on key areas for risk reduction versus defining the entire parameter space). DOE coupled with estimation theory could help determine the minimum number of computations or test points to reduce uncertainties in areas of interest on the response surface. Finally, the areas of residual uncertainty become the primary interest for focused flight testing, which serves to reduce the overall workload for that phase of testing. In this manner, the overall amount of testing could be dramatically reduced with a commensurate effect on total cycle time.

The integration of multidisciplinary data is key to developing this aggressive approach to minimizing data requirements. Multidimensional meta-models can be automatically constructed using limited experimental or numerical data, including data from heterogeneous sources such as CSE, ground test, and flight test. Recent progress in multidimensional response surface technology provides the ability to interpolate between sparse data points in a multidimensional parameter space. These analytical representations act as surrogates that are based on and complement higher fidelity models and/or experiments, and can include technical data from multiple fidelity levels and multiple disciplines (Riesenthaal et al. 2006).

The mathematics of the DOE methodology helps ensure the optimum data set is taken. The alpha and beta (or power coefficients) of the DOE process can be used to address how much further variance can be reduced on the response surface by an additional calculation, wind tunnel test, or flight test. There is a point at which doing another CFD solution will not reduce uncertainty further; hence, one needs to move on to wind tunnel testing. Likewise, there is a point of diminishing returns for doing another wind tunnel test, and the program needs to move on to flight testing. Thus, unnecessary modeling and/or testing can be minimized. Estimation theory (Deyst 2002) can be used to estimate the unit cost of further reductions in uncertainty leading to an optimum strategy for combining testing and modeling. The DOE beta coefficient also provides some insight into the probability that a defect is being passed downstream to the next development step.

The response surface method also provides an invaluable approach to supporting integrated developmental testing (DT) and operational testing (OT) as well as addressing networking and interoperability issues. The characteristics of the vehicle captured in the response surface can be translated directly into the performance math engine for a manned flight simulator as suggested in *Figure 3*. Even at the earliest phases of development, a manned flight simulator can start to address some of the operational integration issues, thereby allowing integrated DT/OT earlier in the program. If early brass-board or digital models of the avionics and communications packages are brought into the manned flight simulator, the evolving performance of the system can be evaluated as a node in a distributed mission simulation. Feedback from this integrated approach can be used in the very early stages to improve the design for maximum performance as an interoperable system. Today, most of the OT interface

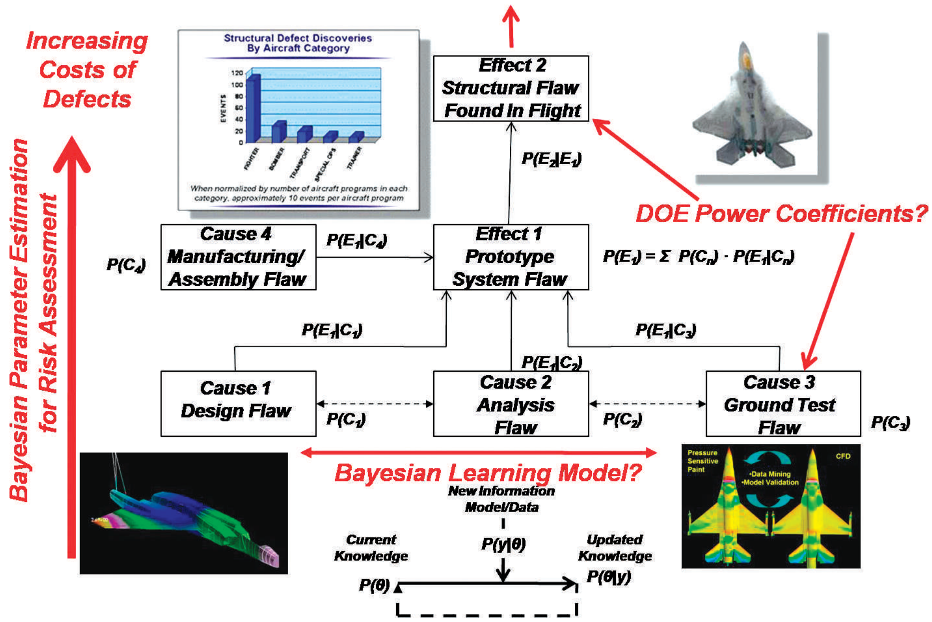

Figure 4. Root cause analysis to avoid late defect discovery.

issues as well as interoperability are not addressed until very late in the development process. The overall impact on reducing development cycle time using such an innovative approach could be immense.

Decreasing late defects

Defects discovered late during the development process not only increase cycle time but also can impact manufacturing costs if significant tooling and production have already occurred. Since concurrent engineering is routinely used to reduce procurement cycle time, almost always tooling and initial production are in progress by the time flight testing occurs.

The challenge to reducing late defect discovery is to determine the root cause for reoccurring late defects. A prime example for the need to better understand the root cause for late defects is the frequency of structural failures discovered during flight testing, even after numerous hours of analysis and wind tunnel testing were used to design the aircraft structure. On average, 10 structural failures are uncovered during flight testing irrespective of the type of aircraft. In addition, many flight systems resize control surfaces after discovering inadequate control authority during flight testing. Working control surface sizing and structural issues this late in development can lead to significant delays in completion and considerable cost increases. Frequently, the late defects in structure or control surface size are looked upon as unique circumstances for the current vehicle in testing. However, by evaluating multiple systems, it is clear that there may be more systemic causes for these late defects.

A suggested approach to combining modeling and testing to reduce systemic late defects is illustrated in *Figure 4*. Using Bayesian statistics, the probability of finding a structural flaw in flight is an accumulation of the probabilities of a flaw being overlooked either in design, analysis, ground testing, or assembly of the prototype flight article. Since the flight test occurs several years after the design and ground testing phases, a root cause analysis of structural failures traceable back to the design, analysis, or wind tunnel testing phase is essentially never done. Consequently, these systemic issues show up in program after program.

The first step in reducing the discovery of late structural defects is to identify the reoccurring structural problems across multiple programs. (This reinforces the need for a monopsony approach by the government to establish a knowledge base of late defects and root causes.) Second, the systemic issues need to be traced back to the source of the defect (i.e., the design, the analysis, or ground testing). CSE can be a major enabler for helping to assess the potential root causes.

Multidiscipline, high-fidelity CFD/CSD can be used earlier in the design cycle to examine interactions between the airframe and structure Traditionally, pressure loads data were obtained on a very early (and expensive) wind tunnel model specifically designed with hundreds to a few thousand pressure taps on the surface of the model. These pressure loads were provided to the structural engineers to perform a structural analysis and design of the vehicle. While the structural engineers are doing their analyses, the aerodynamicists are usually continuing to refine the outer mold lines of the vehicle to improve performance. Because of the cost and complexity of wind tunnel pressure models, effects on pressure loads due to changes in outer mold lines were usually not updated. When the airframe and underlying structure were integrated into the first set of flight vehicles, it was not uncommon to find structural flaws. Contributing to these late discoveries are inadequate characterization of the dynamic interactions between fluids and structures as well as a lack of integration of aerodynamic and structural analysis tools.

Modern wind tunnel testing implements the use of Pressure-Sensitive Paint (PSP) instead of physical pressure taps (Sellers 2005). PSP offers the opportunity to provide cost-effective updated structural load information as the aerodynamic shape of the vehicle changes. Coupled with an integrated CFD/CSD modeling of the airframe/structure, it will be possible to better define the static and dynamic structural loads prior to the first flight. This dynamic interaction between modeling and wind tunnel testing can be incorporated into Bayes' equation as an iterative learning tool to reduce uncertainties in the results from the analysis or wind tunnel test as suggested in *Figure 4*. Using Bayes' equation in an iterative fashion between CSE and wind tunnel testing should minimize the probability of uncertainties being passed downstream in the development process. In addition, DOE power coefficients, if properly applied, should be able to quantify the probability of a defect being passed downstream to flight.

Bayesian statistics can also be used to help a program manager better assess the risk to the program of permitting known design issues to be unresolved until later in the development cycle. The trade space between cost, schedule, and the potential impact of a late defect can be assessed using Bayesian statistics to define a value proposition relative to the design cycle.

Finally, CSE can be an invaluable tool to ensure better use of ground test facilities to preclude design defects from finding their way into the flight test program. Use of CSE to account for Reynolds number scaling effects and potential bias errors such as wind tunnel wall interference is well understood and effectively applied. An area where scaling effects are not well understood and CSE may have the potential for producing new insights is simulation of military tactical aircraft at high-angle maneuvering conditions. In these conditions, the flow is dominated by vortex structures and flow separation. Surprisingly, a large number of tactical military aircraft have required significant modification to control surface size or structure even after a comprehensive wind tunnel campaign. Changes of this magnitude during the flight test program can have a profound effect on program cost and schedule. Coupled effects on manufacturing costs can also become significant during this phase.

There exists a strong potential that a root cause for these late defect discoveries may be the lack of understanding of scaling principles for vortex-dominated or separated-flow phenomena. The general Reynolds number scaling principles used today were developed in the mid '70s from attached flow data taken on commercial transport aircraft configurations. At the time, computational tools as well as flow diagnostics were not capable of supporting more in-depth understanding of separated-flow phenomena.

At high angles of attack, flow separation from the leading edge can create vortex structures that impinge on vertical tails. The appearance and interaction of these vortices with the vehicle can strongly influence control authority or cause structural failures. The classical wing-drop roll-control problem for the F-18 was caused by vortex-shock interactions. Vertical tail structural flaws caused by vortex impingement and breakdown have been discovered on a number of twin-tail flight vehicles, including the F-22.

In the wind tunnel, the model is generally geometrically scaled. If one examines the leading edge vortex formation and separation for a typical tactical fighter at high angle of attack there are at least five characteristic lengths involved in the problem: chord length, leading edge radius, boundary layer displacement thickness, vortex core diameter, and vortex breakdown length. It is not clear whether these are dependent- or independent-length scales, which begs the question of whether geometric scaling is sufficient to model vortex-dominated or massively separated–flow phenomena. Current CSE tools, including large eddy simulations, have been used to model vortex effects on aircraft at high angles of attack (Morton 2009). Coupled with advanced off-body flow laser diagnostic tools like Planar Laser-Induced Fluorescence (PLIV) (Ruyten 1994) CSE could provide an integrated computational/experimental approach to understanding better the causative effects of the various length scales and better predict flight conditions from wind tunnel data.

Early subsystem integration

Another key to increasing the quality, q, or decreasing the amount of rework, is earlier and better integration of major subsystems such as the airframe/structure, the airframe/propulsion systems, or the airframe/weapon systems. Most defects occur at the interface of major subsystems. Current practices generally address system integration issues later in the development process, which maximizes the amount of rework required (and increases associated costs) if a defect is discovered. Key enablers required to get earlier insights into integration issues include high-fidelity, multidisciplined modeling capabilities. These multi-discipline tools are being developed in the CREATE-AV program described earlier.

Integration of CSE with testing for airframe/weapon integration is already a mature capability. As mentioned earlier the AFSEO has a monopsony on the air armament certification process. As a consequence, CSE, wind tunnel testing, and flight testing have been highly integrated since 1988 (Kraft 1994; Carlson, King, and Patterson 1995; Dean et al. 2007; Keen et al. 2009; Cenko 2009; and Kraft 1995). However, the Seek Eagle certification process occurs after an air vehicle is developed, so the tools are used to identify issues and avoid parts of the flight envelope where the weapon and the airframe may not be optimally integrated.

The tools and capabilities developed with the government to support airframe/weapon integration have migrated to use by industry as well. However, these advanced modeling tools are not used as an integral part of the early design cycle for a new flight system. This is partially driven by the fact that the entire inventory of air armament to be carried by a new platform is not necessarily defined during the system development phase. However, basic inventory weapons should be integrated into the earliest design phases to ensure compatibility downstream. This would decrease the probability of finding interface issues between the airframe and weapon systems much later in the development cycle.

Airframe/structure integration is arguably the most important of the integration issues that need to be resolved early in the design cycle. The static and dynamic interactions between aerodynamic flow around the vehicle and structural integrity of the system are a major driver in weight management for the vehicle as well as sizing of control surfaces. Weight management over the development cycle is a major causative factor for rework and cost escalation. Many of the key performance parameters guiding development of the system are affected by vehicle weight. Resolving weight issues late in the development cycle also can impact determination of the Reliability, Availability, and Maintainability (RAM) of the system prior to fielding. RAM is one of major causes for a system to be determined to be unsuitable for fielding.

The application of peta-scale computing in the near future will enable integrated modeling of aerodynamics and structures during the design process. The tools to do this are being developed under the OSD CREATE-AV program. The ability to integrate these multiple disciplines will address many of the subsystem issues early on (i.e., the subsystems will be designed for an integrated environment). Having advanced diagnostic tools such as PSP in ground-test facilities will not only enable model validation but will also better help characterize the dynamic flow field effects on flight vehicle structures. PSP will also permit rapid updating of flow field loads as part of structural analyses without having to build or update pressure models. As discussed earlier, better connectivity between advanced modeling and wind tunnel testing needs to occur early and often prior to first flight to avoid discovery of structural issues late in the program.

Minimizing potential weight growth of the airframe structure to account for defects discovered in flight can also have an important effect on the development of the propulsion system. Frequently, when weight growth occurs late in the development cycle because of structural changes, the propulsion system developers are tasked to produce more thrust to ensure meeting vehicle performance parameters. It is not uncommon for the engine developer to have to significantly improve the performance of the engine fairly late in the development cycle. All of these interactive weight issues also impact control surface effectiveness and control system gains. This vicious interplay between the various subsystems is a contributor to late cycle churn and program delays.

There is also the potential for sharing some of the same modeling methodologies between the structural analysts and the propulsion system designers. The fluid-structure interactions that drive structural design exhibit the same fundamental physics as the fluid-structure interactions on the aeromechanics of fan and compressor blades. Advances in integrated CFD/CSD tools will help better understand and avoid potential high-cycle fatigue issues earlier in the design cycle.

Detailed modeling of a turbine engine is the more challenging of the CSE capabilities under development. With hardware and software advances to peta-flop scales, it is becoming feasible to model detailed rotating machinery such as the first stages of a fan on a turbine engine. Coupled with a detailed model of the flow field around the aircraft and inlet, it will be possible to model the integration of the turbine engine with the airframe and inlet configuration. Current capabilities and practices design and develop the engine independent of the airframe and try to account for integration issues discovered during testing. Frequently these issues are not fully discovered until after first flight.

The discussions in this section present an aggressive use and integration of modeling and testing simulation methodologies to change the future effectiveness of aeronautical development. It is clear that various test capabilities cannot be addressed and judged in isolation but have to be treated as an integral combination with technical expertise, improved processes, and better test methods to achieve the desired state of effectiveness. In addition, they will have to be applied in a common environment to ensure gains in effectiveness can be replicated from program to program.

Conclusions

High-performance computing has advanced to a state that should support more applications of CSE in the aeronautical system development process. With such advances, a national debate has reemerged on using CSE to replace testing. The author argues that a national discussion of replacing testing with CSE is misguided. The nation would be better served by putting our energy into determining approaches to fully integrate CSE with testing to reduce the cycle time for aeronautical system development. To successfully integrate CSE and testing will require advances not only in high-performance computing but in intellectual capital and process management as well. Key recommendations for advancing the use of CSE are as follows:

- Most important, the government has to adopt a monopsony for the application of CSE to the development process for military flight systems.
- A common architecture for the application of multidisciplinary computational tools in a high-performance computing environment needs to be adopted by the industry. This architecture should not preclude use of proprietary physical models from industry but should enable CSE and testing to be optimized for use across any aeronautical development process.
- In spite of the computer hardware systems advances, there is still much work to be done in building the software tools to best use the advanced computer systems; notably, better physics modeling, scalability of solvers to tens of thousands of processors, and better multidisciplinary modeling to enable dynamic simulation of complete maneuvering aircraft.
- CSE alone will not provide maximum impact to cycle time reduction but must be integrated with other tools such as design of experiments, streamlined test methodologies, advanced diagnostic tools, networking, and knowledge management.
- In addition, a concept of operations and the necessary computing capacity need to be developed to support the aeronautical systems engineering process. ❑

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References

Andrew, W. Geoffrey. May 2001. Do modern tools utilized in the design and development of modern aircraft counteract the impact of lost intellectual capital within the aerospace industry? Master's thesis, MIT.

Benek, John A., and Edward M. Kraft. 1996. The changing role of wind tunnel testing and computational fluid dynamics in the development of flight vehicles, AIAA paper 96-3349. Presented at the Second Test and Evaluation International Aerospace Forum, June 25–27, London, United Kingdom.

Carlson, D. R., M. O. King, and R. C. Patterson. 1995. Integrated store separation and ballistic accuracy: Applying enabling technologies to improve aircraft store separation, AIAA paper 95-3431-CP. Presented at AIAA Atmospheric Flight Mechanics Conference, August 7–10, Baltimore, Maryland.

Cenko, A. 2009. Lessons learned in 30 years of store separation testing, AIAA paper 2009-98, 47th AIAA Aerospace Sciences Meeting, January 5–8, Orlando, Florida.

Chapman, Dean R. 1979. Computational aerodynamics development and outlook. Dryden Lectureship in Research. *AIAA Journal* 17 (12): 1293–1313.

Dean, J., S. Morton, D. McDaniel, and S. Goetz. 2007. Efficient high resolution modeling of fighter aircraft with stores for stability and control clearance, AIAA paper 2007-1652. Presented at 2007 USAF T&E Days, February 13–15, Destin, Florida.

Dean, John P., Scott A. Morton, David R. McDaniel, James D. Clifton, and David J. Bodkin. 2008. Aircraft stability and control characteristics determined by system identification of CFD simulations, AIAA paper 2008-6378. Presented at AIAA Atmospheric Flight Mechanics Conference and Exhibit, August 18–21, 2008, Chicago, IL: AIAA.

Deyst, John D. 2002. The application of estimation theory to managing risks in product developments. In *Proceedings of the 21st Digital Avionics Systems Conference,* October 27–31, 2002, Irvine, CA. Vol. 1. Piscataway, NJ: AIAA/IEEE.

Drezner, J. A. 1992. Maintaining future military aircraft design capability. RAND Report R-4199-AF.

Hansen, James R. 1986. *Engineer in charge – A History of the Langley Aeronautical Laboratory, 1917–1958*. NASA History Series, NASA SP 4305. Washington, D.C.: NASA History Office.

Keen, K. S., C. H. Morgret, T. F. Langham, and W. B. Baker, Jr. 2009. Trajectory simulations should match flight tests and other lessons learned in 30 years of store-separation analysis, AIAA paper 2009-99. Presented at the 47th AIAA Aerospace Sciences Meeting, January 5–8, Orlando, Florida.

Kraft, E., and G. Chapman. 1993. A critical review of the integration of computations, ground tests, and flight test for the development of hypersonic vehicles, AIAA paper 93-5101. Presented at the AIAA/DGLR 5th International Aerospace Planes and Hypersonics Technologies Conference, November 30–December 3, Munich, Germany.

Kraft, Edward M., and Arthur F. Huber, II. 2009. A vision for the future of aeronautical ground testing. *The ITEA Journal of Test and Evaluation* 30 (2): 237–250.

Kraft, E. M. 1994. Combining ground test, computational fluid dynamics, and flight tests to improve aircraft/weapons integration, AIAA paper 94-2660. Presented at 25th Fluid Dynamics Conference, May 31–June 2, London, United Kingdom.

Kraft, E. M. 1995. Integrated test and evaluation—A knowledge-based approach to system development, AIAA paper 95-3982. Presented at First AIAA Aircraft Engineering, Technology, and Operations Congress, September 19–21, Los Angeles, California.

Kraft, E. M., and Jere J. Matty. 2005. Application of high performance computing at the Arnold Engineering Development Center (AEDC). *ITEA Journal* 26 (2): 55–60.

Landman, Drew, Jim Simpson, Dan Vicroy, and Peter Parker. 2007. Response surface methods for efficient aircraft configuration aerodynamic characterization. *Journal of Aircraft* 44 (4): 1189–1195.

Mavriplis, D. J., D. Darmofal, D. Keyes, and M. Turner. 2007. Petaflops opportunities for the NASA Fundamental Aeronautics Program, AIAA paper 2007-4084. Presented at the 18th AIAA Computation Fluid Dynamics Conference, June 25–28, Miami, Florida.

Melanson, Mark R. 2008. An assessment of the increase in wind tunnel testing requirements for air vehicles over the last fifty years, AIAA paper 2008-830. Presented at 46th AIAA Aerospace Sciences Meeting and Exhibit, January 7–10, Reno, Nevada.

Morton, Scott. 2009. Detached-eddy simulations of vortex breakdown over a 70-degree delta wing. *Journal of Aircraft* 46 (3): 746–755.

Morton, Scott A., David R. McDaniel, David R. Sears, Brett Tillman, and Todd R. Tuckey. 2009. *Kestrel*—A fixed wing virtual aircraft product of the CREATE program, AIAA paper-2009- 0338. Presented at the 47th AIAA Aerospace Sciences Meeting, January 5–8, Orlando, Florida.

Reisenthel, P. H., J. F. Love, D. J. Lesieutre, and R. E. Childs. 2006. Cumulative global metamodels with uncertainty—A tool for aerospace integration. *The Aeronautical Journal* 110 (1108): 375–384.

Ruyten, W. M., D. O. Williams, and F. L. Heltsley. 1994. Computational flow imaging for planar laser-induced fluorescence applications, AIAA paper 1994-2621.

Sellers, Marvin E. 2005. Advances in AEDC's lifetime pressure-sensitive paint program, AIAA paper 2005-7638. Presented at U.S. Air Force T&E Days, December 6–8, 2005. Arnold Air Force Base, Tennessee.

Sheeley, J. M., D. A. Sells, and E. J. Felderman. 2010. Requirements for fly-the-mission control in aerodynamic wind tunnels, AIAA paper 2010-1306. Presented at the 48th AIAA Aerospace Sciences Meeting, January 4–7, Orlando, Florida.

Tinoco, Edward N. 2008. Validation and minimizing CFD uncertainty for commercial aircraft applications, AIAA paper 2008-6902. Presented at the 26th AIAA Applied Aerodynamics Conference, August 18–21, Honolulu, Hawaii.

Vassberg, J. C., E. N. Tinoco, M. Mani, O. P. Brodersen, B. Eisfeld, R. A. Wahls, J. H. Morrison, T. Zickuhr, K. R. Laflin, and D. J. Mavriplis. 2008. Abridged summary of the Third AIAA Computational Fluid Dynamics Drag Prediction Workshop. *Journal of Aircraft* 45 (3): 738–749.